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Optimum Depth of Propagation in Shallow Water

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A numerical simulation study was conducted to determine the receiver depth which would maximize the signal-to-wind noise ratio for one of several source depths in various shallow water environments. The environments were chosen to cover the full range typically found in shallow water: four sediment types ranging from fine sand to silty clay, three sound-speed profiles in the water column (isovelocity, positive gradient, and negative gradient), source depths within and below the gradient in the water sound-speed profile, and source frequencies in octaves from 50 to 800 Hz. For

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20. ABSTRACT (Continued)

each case, a transmission-loss model and a wind-noise model were run. The results were then combined to yield a signal-to-noise level. By using a contouring technique, the data were reduced sufficiently to interpret the effects of the source depth, bottom type, velocity structure in the water column, and source frequency on the location of the optimum receiver depth. For frequencies above 200 Hz, the optimum depth was nearly independent of frequency and sediment type. In most cases, the optimum depth was equal to the source depth. In 75% of the cases the optimum depth was middepth or below. The location of the best signal-to-noise ratio (S/N) was in most cases independent of the wind-noise field.

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OPTIMUM DEPTH OF PROPAGATION IN SHALLOW WATER

INTRODUCTION

In practical underwater acoustic propagation measurements, the acoustic signal is always detected against a noise background, usually dominated by the ocean ambient noise. Thus a quantity of interest in propagation problems is the ratio of the signal level to the noise level, S/N. In shallow water, the signal level and the noise level are strongly influenced by environmental conditions, particularly the sound-speed profile in the water column, the sea state, the wind speed, and the structure and acoustic properties of the bottom. In addition, the signal level depends on the distance between the source and receiver and on their respective depths, while the ambient noise level depends on the strength and distribution of the noise sources and on the depth of the receiver. Of the many quantities influencing the S/N, often only the receiver depth can be controlled. The problem then is to determine the receiver depth which maximizes the S/N for a specific source depth.

The solution to this problem depends on the amount of information available about the environmental properties and the depth of the source. Assuming that the prediction models used correctly account for the features of the propagation and noise problems, a complete set of environmental data (as required by the models) and knowledge of the depth and range of the source would allow an accurate prediction of the optimum receiver depth. With incomplete data, or no data at all, it is still possible to make useful predictions of the probable optimum depth.

In this report numerical models are used to generate transmission-loss and wind-noise levels for a variety of typical sound-speed profiles and bottom types. These results are combined to give the relative S/N as a function of depth for a number of sets of environmental conditions often found in shallow water. From these, the optimum receiver depth is obtained as a function of source depth. The results are analyzed to determine the factors controlling the optimum depth. Finally conclusions are drawn as to the dependence of the optimum receiver depth on the environment.

THEORY

The transmission-loss model used in this study is based on a normal-mode representation of the acoustic field [1]. The wind-noise model, which is based on the same normal-mode model, is a computer implementation of the theory described in Ref. 2. Both models include the following features of the shallow water environment: depth-dependent sound speed in the water column and sedimentary layer, absorption in the water column and bottom, and attenuation due to roughness at the surface and at the bottom interface.

The transmission loss (TL) is defined by the equation

$$S = S_o - TL, \tag{1}$$

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where S is the received signal level and S_o is the source level; both quantities are expressed in dB referenced to 1 μPa. Similarly it will be convenient to define the quantity W by the equation

$$N = N_o + W, \tag{2}$$

where N is the received wind-noise level and N_o is a source level for wind-generated noise. The S/N is

$$S - N = S_o - N_o - (TL + W), \tag{3}$$

from Eqs. (1) and (2). Since we are interested in the depth dependence of the S/N, we define the relative signal-to-noise level by the equation

$$R = -(TL + W). \tag{4}$$

The quantities TL and W are outputs of the transmission loss and wind-noise models. Both TL and W contain the environmental dependence of the received signal and noise levels plus their dependence on receiver depth. In addition TL depends on source depth.

CALCULATION PARAMETERS

Figure 1 shows the three generic water sound-speed profiles used in the calculations: negative gradient, isovelocity, and positive gradient located within the 100-m water column. For each profile, calculations were made for four bottom types: fine sand, sandy silt, sand-silt-clay, and silty clay. The sediments selected span nearly the full range of sediment types found in shallow water [3]. Table 1 lists the accoustical properties of these sediments. Reference 3 presents the sound-speed profiles used in the sediment (Fig. 1a). In addition, a surface wave height of 0.3 m rms, corresponding to sea state 3, was assumed. For each water sound-speed profile and bottom-type combination, calculations were made at five frequencies: 50, 100, 200, 400, and 800 Hz, with source depths at 25 and 50 m. The transmission loss and noise results were combined to get relative S/Ns at 25 km, and from these the optimum depths were determined.

Table 1. Properties of Sediment Types Modeled

Sediment Type	Density(gm/cm^3)	Porosity(%)	Velocity Ratio[a]
Fine Sand	1.941	45.6	1.145
Sandy Silt	1.771	54.1	1.080
Salt-Silt-Clay	1.596	66.3	1.033
Silty Clay	1.421	75.9	0.994

[a]Velocity Ratio = velocity in the sediment/velocity in seawater (measured at the water-sediment interface)

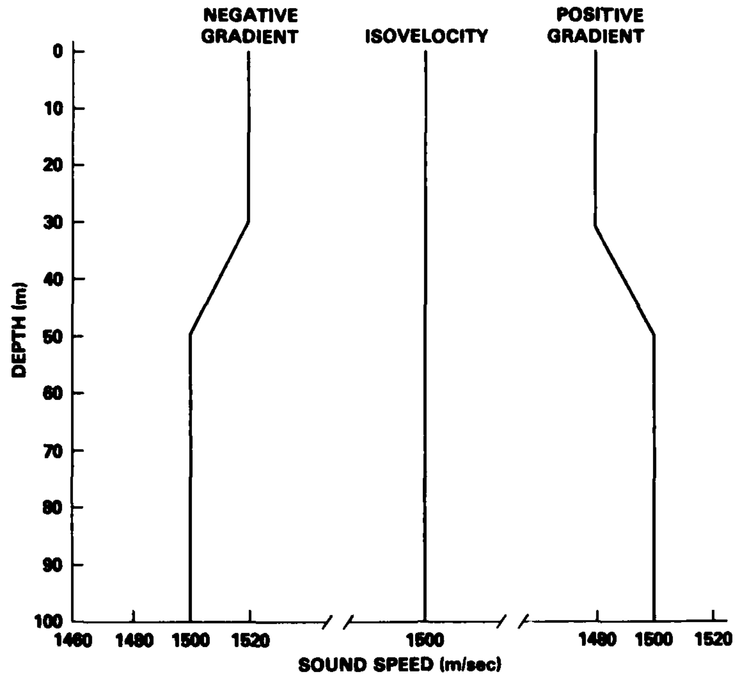


Fig. 1(a) — The three generic sound-speed profiles used in the calculations: negative gradient, isovelocity, and positive gradient

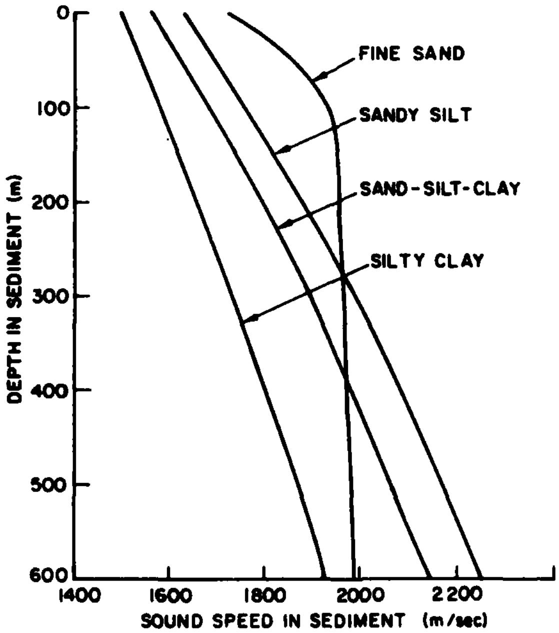


Fig. 1(b) — The four sound-speed profiles in the sediments used in the calculations: fine sand, sandy silt, sand-silt-clay, and silty clay

TRANSMISSION LOSS RESULTS

In most cases, our calculations show that the minimum incoherent transmission loss is located with the receiver at the same depth as the source. (The incoherent loss is obtained by adding the energy contributions of the individual modes as opposed to the coherent loss where the phased pressures are added). This result agrees with the results which Weston [4] and Buckingham [5] obtained on theoretical grounds. The degree of the localization of the low-loss region within the water column is dependent upon the number of modes that made up the modal acoustic field. For the cases modeled, typically eight to ten modes are present in the modal acoustic field when a well-defined region of minimum transmission loss occurs. An example of this effect is shown in Fig. 2. Incoherent loss is plotted as a function of receiver depth at three different ranges (10, 25, and 50 km). The source is at middepth (50 m) and emitting at 800 Hz. The sound-speed profile has a negative gradient, and the sediment is fine sand. It is readily apparent that the depth at which loss is a minimum at the three different ranges is at the sourced depth, and the relative level of transmission loss as a function of depth in the water column is nearly independent of the ranges modeled (10 to 50 km). (The range independence of the relative level of transmission loss as a function of depth at a particular frequency in the water column was found in all of the cases modeled). Also note that the loss is considerably higher in the upper portion of the water column than in the lower half. This is an important point that will be addressed later.

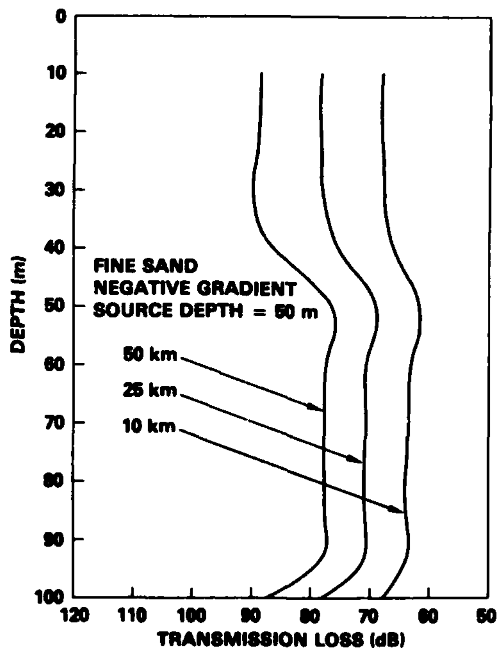
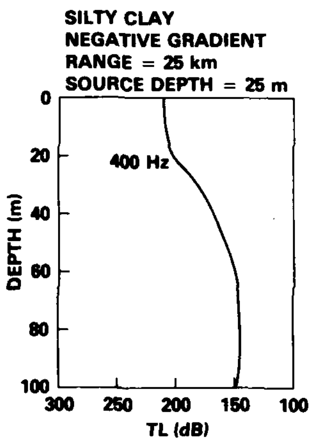


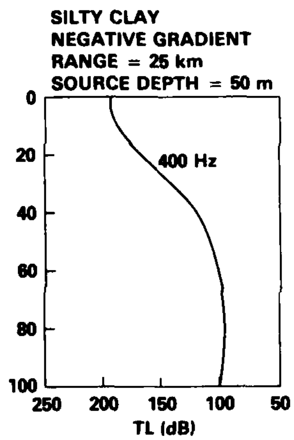
Fig. 2 — Incoherent transmission loss as a function of depth for ranges of 10, 25, and 50 km. The source is at 50 m and emitting at 800 Hz. The sound-speed profile is a negative gradient and the sediment type is fine sand.

Similar plots of transmission loss vs depth were made for all combinations of source depths, frequencies, sediment types, and sound-speed profiles. In all of the cases, the location and relative strengths of peaks were very similar for the three sandy sediments modeled (fine sand, sandy silt, sand-silt-clay). Thus for the purposes of this study, the propagation environments can be reduced to sandy type bottoms and silty clay-type bottoms, each with isovelocity, negative gradient and positive gradient sound-speed profiles in the water column.

From the large collection of cases modeled, only two yielded broad regions of locally low loss that remained in the same portion of the water column independent of source depth. The two cases were for the silty clay sediment with a negative gradient profile with source depths at 25 and 50 m as shown in Fig. 3. In both of these cases the first mode greatly dominated the acoustic field. Because there is essentially only one mode, the depth associated with minimum loss is independent of source depth. The minimum loss is located approximately where the mode itself is a maximum (see Fig. 4).



(a) Fine-sand sediment



(b) Silty-clay sediment

Fig. 3 — Incoherent transmission loss as a function of depth at 25-km range. The sound-speed is a negative gradient, the source is 400 Hz, and the sediment type is silty-clay.

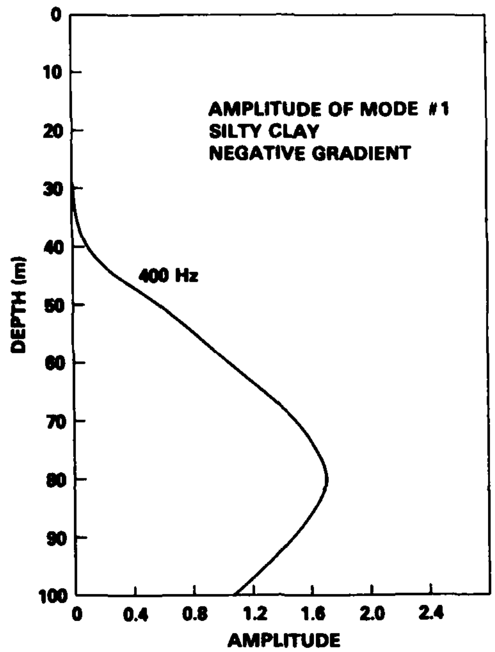


Fig. 4 — Mode amplitude as a function of depth of the single contributing mode to the signal field for the case shown in Fig.3

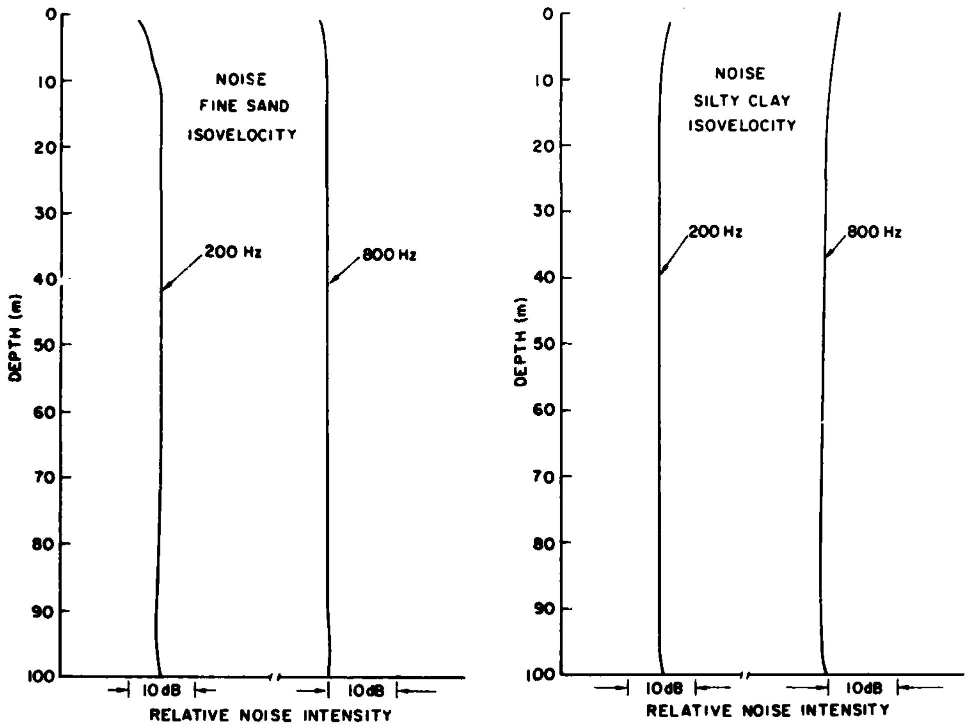
WIND-GENERATED NOISE RESULTS

For a given sound-speed profile, the calculated relative noise intensity distribution (*NL* in Eq. 4) as a function of depth is insensitive to the different bottom types modeled. However the absolute intensities were higher for the less attenuating sands (by 3 to 4 dB) (Fig. 5a) than for silty clay bottoms (Fig. 5b).

The positive gradient has a significant effect on the distribution of wind-generated noise in the water column. The calculated noise level was as much as 5 to 10 dB greater above the gradient than below the gradient. The depth dependence of noise level is especially evident at 100 and 200 Hz (Fig. 6). This level difference is due to the lower order modes being trapped above the sound-speed gradient. The effect of the positive gradient is to allow only negligible interaction of these low-order modes with the bottom; hence, there is relatively little bottom attenuation of these modes. The result is that the lower order modes dominate the acoustic noise field in the upper portion of the water column. In fact at 100 Hz it is only the first mode that contributes significantly to the noise field. Below the gradient the contribution of the low-order modes is negligible.

In downward refracting gradients, the noise intensity distribution exhibits a small maximum near the surface and a small minimum near the bottom. This level difference is greatest between 50 and 200 Hz and is typically 2 to 4 dB.

For isovelocity water, the noise level is nearly constant throughout the entire water column for each frequency.



(a) Fine-sand sediment

(b) Silty-clay sediment

Fig. 5 — Relative intensity of wind-generated noise as a function of depth at 200 and 800 Hz. The sound-speed profile is isovelocity.

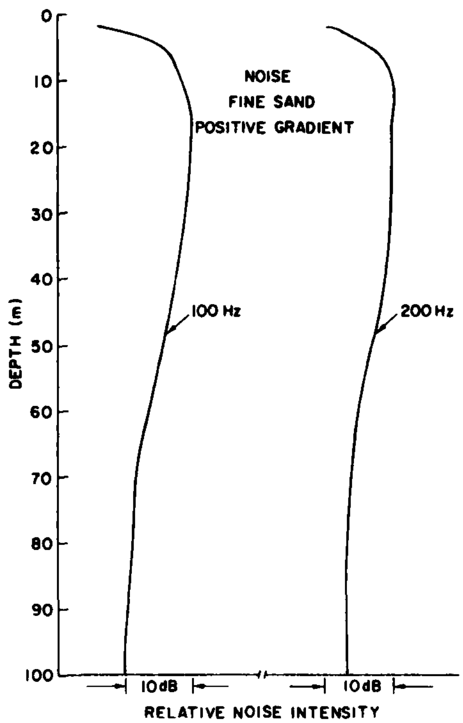


Fig. 6 — Relative intensity of wind-generated noise as a function of depth at 100 and 200 Hz. The sediment type is fine sand and the sound-speed profile is a positive gradient.

OPTIMUM DEPTH ANALYSIS

To understand the various environmental effects on propagation in shallow water from a numerical simulation study, one must assimilate a rather large amount of data. It is necessary to retain enough of the data to arrive at meaningful conclusions, while not retaining so much as to be inundated with extraneous information. This dilemma is highlighted by the following two examples.

First, we return to the transmission loss curves shown in Fig. 2. The source is at middepth and emitting at 800 Hz. The water sound-speed profile is that of a negative gradient above a fine sand sediment. Obviously the minimum transmission loss occurs at middepth and, as mentioned previously, there is significantly less loss below than above the middepth point. In fact the minimum loss at 50 m is less than 2 dB below the broad region of loss located below middepth. Thus, the received signal level is relatively insensitive to displacements in receiver depth below middepth. This is the type of information that should be retained when synthesizing the general conclusions about transmission loss applicable for cases that are similar, but not quite the same as those modeled.

The second example (Fig. 7) is that of a S/N plotted as a function of depth at five different frequencies. This example highlights the problem of locating the generally best or optimum depth as a function of frequency while still retaining information about the sensitivity of the field to displacements in the vicinity of the optimum depth. This example is typical of cases where a velocity gradient exists in the water column in the sense that superficially the curves bear little resemblance to each other at the different frequencies. One is tempted to look only at the depths of optimum signal to noise for each frequency to draw general conclusions as to the frequency dependence of the signal-to-noise field for this particular environment. If we retain only the point in depth with highest S/N, this would greatly simplify the problem, although in the process one would lose information about the signal-to-noise fields' sensitivity to local displacements in depth about these maxima.

As shown earlier, the relative signal-to-noise level is defined by the equation

$$R = -(TL + W).$$

The results in this report have been referenced to an arbitrary level as follows

$$S\text{-}N = 100 - (TL + W). \tag{5}$$

The task is to now find the location of the optimum S/N as a function of frequency for a particular environment. In this context, environment refers to the set of fixed conditions needed to calculate the S/N (source depth, sound-speed profile, and sediment type). To differentiate between broad and narrow maxima and to remove locally minor perturbations within the S/N interference field, contours of signal to noise 2 dB below the maximum for a particular environment in a frequency-receiver depth plane have been constructed. The interpretation of the contours of S/N 2 dB below the maximum is: for the particular environment in question, any coordinate (frequency, receiver depth) between the contours is within 2 dB of the maximum S/N for that particular environment. Figures 8 to 11 show the resultant contours of S/N 2 dB below the maximum. The information contained in Figs. 8 to 11 is also listed in Table 2.

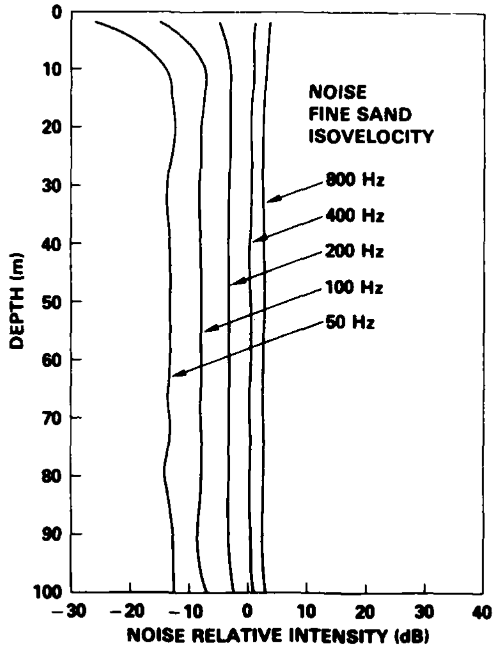


Fig. 7 — S/N as a function of depth at frequencies. The sediment is fine sand, sound-speed profile is positive gradient, source depth is at 50 m, and the range is 25 km.

The simplest method of determining the effect of noise on S/N is to construct contours of transmission loss 2 dB above the minimum (Figs. 12 to 15) in the same manner that the contours of S/N 2 dB below the maximum were constructed. The differences between the two should highlight any influence that the wind-generated noise has on choosing an optimum depth.

By comparing the appropriate contours of S/N 2 dB below the maximum with the contours of *TL* 2 dB above the minimum (Figs. 11 and 15), looking at the positive gradient, the noise tends to lower the region within the contours of S/N 2 dB below the maximum. This is particularly true in the region of 50 to 200 Hz.

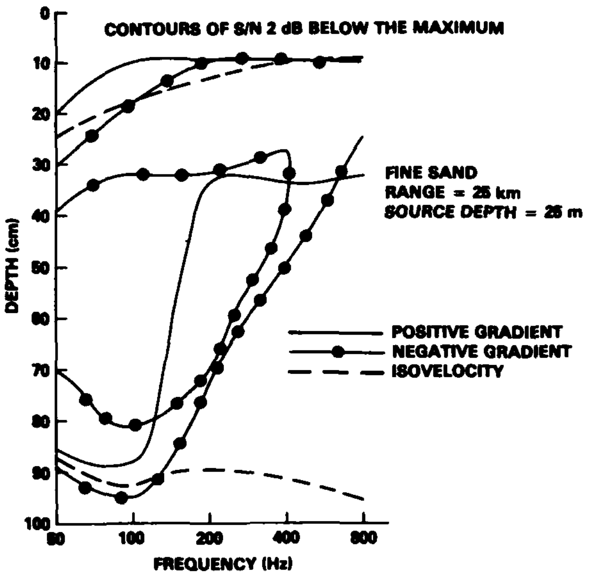


Fig. 8 — Contours of S/N 2 dB below the maximum for fine sand sediment, source depth at 25 m, at a range of 25 km.

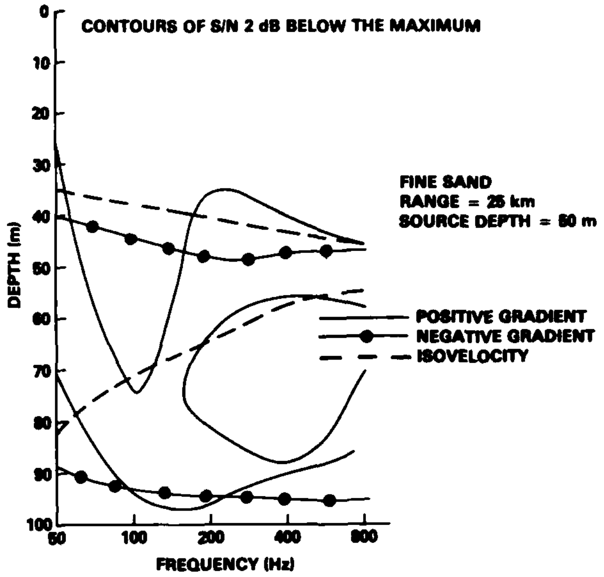


Fig. 9 — Contours of S/N 2 dB below the maximum for fine sand sediment, source depth at 50 m, at a range of 25 km.

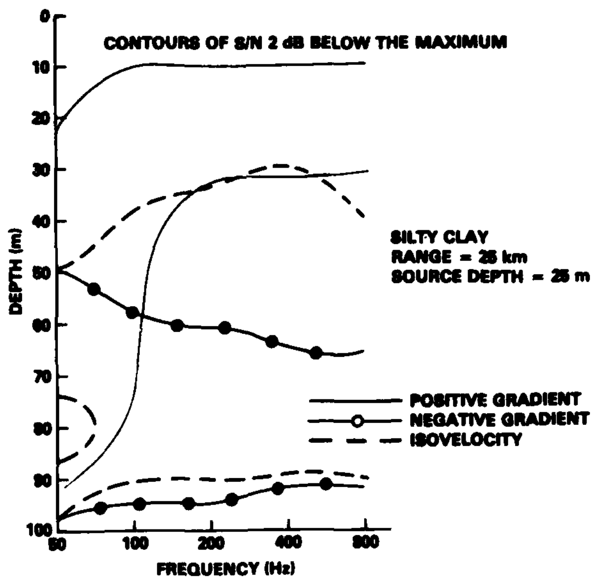


Fig. 10 — Contours of S/N 2 dB below the maximum for silty-clay sediment, source depth at 25 m, at a range of 25 km.

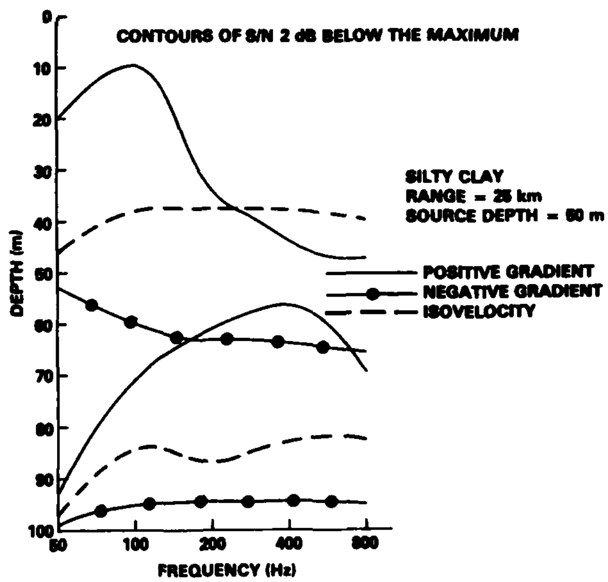


Fig. 11 — Contours of S/N 2 dB below the maximum for silty-clay sediment, source depth at 50 m, at a range of 25 km.

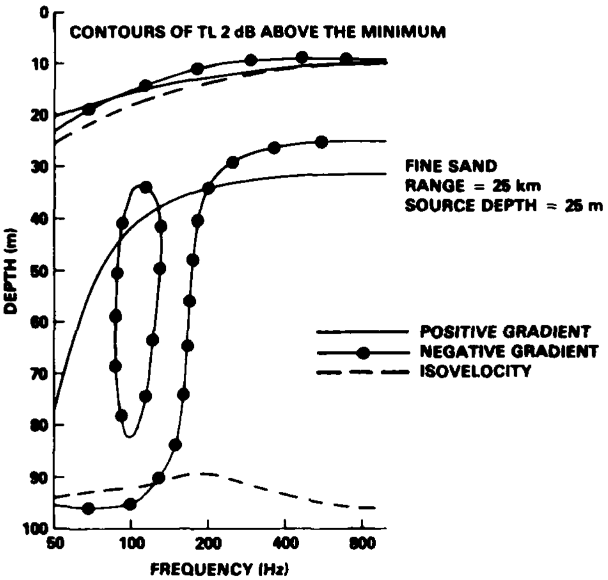


Fig. 12 — Contours of TL 2 dB above the minimum for fine sand sediment, source depth at 25 m, at a range of 25 km.

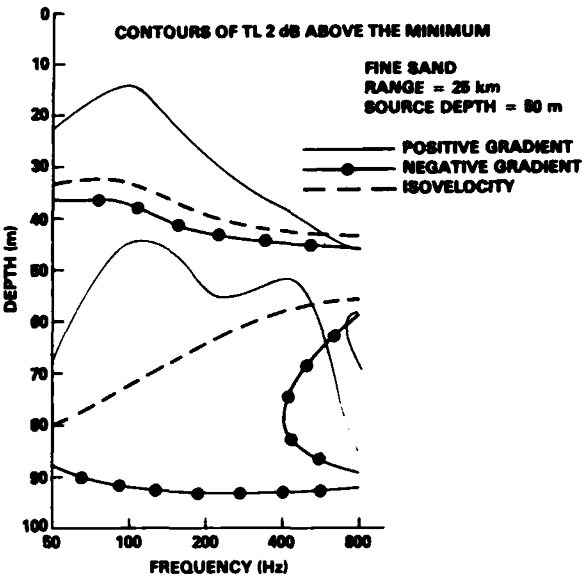


Fig. 13 — Contours of TL 2 dB above the minimum for fine sand sediment, source depth at 50 m, at a range of 25 km.

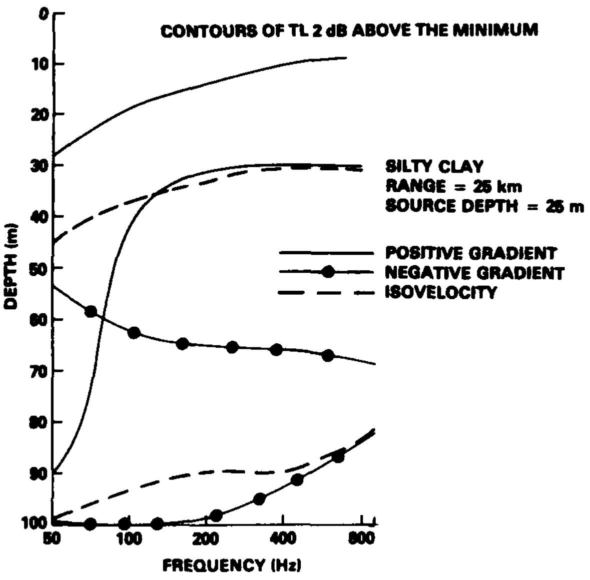


Fig. 14 — Contours of TL 2 dB above the minimum for silty-clay sediment, source depth at 25 m, at a range of 25 km.

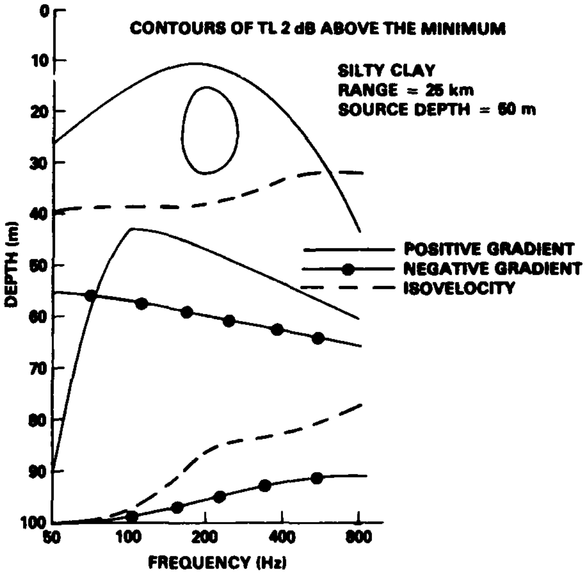


Fig. 15 — Contours of TL 2 dB above the minimum for silty-clay sediment, source depth at 50 m, at a range of 25 km.

Table 2. Approximate Optimal Depth Ranges (m) as Found from the Contours of S/N 2 dB Below the Maximum at 25 km

SD = 25 m, 200 to 800 Hz

Sediment	Positive Gradient	Isovelocity	Negative Gradient
Fine Sand	10-35	10-90	10-30
Silty Clay	10-35	35-90	65-95

SD = 50 m, 200 to 800 Hz

Sediment	Positive Gradient	Isovelocity	Negative Gradient
Fine Sand	40-60, 85-90	40-60	50-95
Silty Clay	45-60	40-85	65-95

DISCUSSION AND CONCLUSIONS

The results embodied in the contours of S/N 2 dB below the maximum provide a high density of information which would be less evident if presented in a less compact form. The environmental effects inferred from the contours are equally valid at receiver ranges other than 25 km due to the range independence of the realtive levels of transmission loss as a function of depth in the water column. Limited sensitivity studies in which the depth and thickness of the channel and the water depth were varied indicate that the results are fairly insensitive to water depth and to small changes in sound-speed profile. Examination of Figs. 8 to 15 leads to the following conclusions:

- The depth of the maximum S/N is nearly the same as the depth of minimum transmission loss. The wind-generated noise has a significant effect only when the source is below a positive gradient. The effect is to deepen the region of maximum S/N by approximately 10% of the water depth above 200 Hz. and to deepend the maximum region to well below mid-depth in the frequency range of 50 to 200 Hz.

- For 200 Hz and above (the region where wind-generated noise often dominates the ocean ambient noise), the optimum depth is nearly independent of frequency.

The following conclusions are valid for frequencies of 200 Hz and above:

- The optimum depth is nearly independent of sediment type. The exception is silty-clay, with a negative sound-speed gradient.

- The optimum depth is equal to the source depth with the following exceptions:

  a. for a negative gradient profile over a silty-clay sediment the optimum depth is well below middepth,

b. for an isovelocity profile over a silty-clay sediment with a source at 25 m, the optimum S/N is found at approximately middepth.

(An explanation for the preceding exceptions (the dominance of the first mode of propagation) is given in the discussion of the transmission loss results.)

- **In the majority of cases (75%), the optimum depth is middepth or below.**

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